NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EFFECT OF WIND NOISE ON UNDERSEA ACOUSTIC NETWORK PERFORMANCE AND DESIGN

by

Christopher Hurt

September 2005

Thesis Advisor:	Joseph A. Rice
Co-Advisor:	Rebecca E. Stone

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE: Effect of Wind Noise on Undersea Acoustic Network Performance and Design			**5. FUNDING NUMBERS**
6. AUTHOR(S) Christopher Hurt, ENS, USN			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

For acoustic frequencies of interest in the development of undersea wireless wide-area networks, wind noise is the dominant contribution to channel noise. The large dynamic range of wind noise forces the network designer to consider wide variations in link margin and effective node-to-node range. Previous reported correlations of acoustic communication performance and wind speed led to multiple hypotheses explaining degradation, including noise variability as well as wind-driven sea-surface effects such as roughness, entrained bubbles, mixing, and stratification. This thesis examines operations of a 40-node wide-area acoustic network in varying noise conditions. This data set is unique in that the environment is strongly downward refracting. Based on theoretical models, wind noise is assumed to dominate all other noise sources. Considerations include dependence of link margin and range on wind speed. Although the experiment was not designed to examine the correlation between transmission range and wind speed, a weak correlation was observed in the limited data set available.

14. SUBJECT TERMS Undersea Noise, Seaweb, Undersea Acoustics, Acoustic Communications, Link Budget, METOC Impacts			**15. NUMBER OF PAGES** 76
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

i

THIS PAGE INTENTIONALLY LEFT BLANK

**EFFECT OF WIND NOISE ON UNDERSEA ACOUSTIC NETWORK
PERFORMANCE AND DESIGN**

Christopher S. Hurt
Ensign, United States Navy
B.S., United States Naval Academy, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ACOUSTICS

from the

**NAVAL POSTGRADUATE SCHOOL
September 2005**

Author: Christopher Hurt

Approved by: Joseph A. Rice
                 Thesis Advisor

                 CDR Rebecca Stone, USN
                 Co-Advisor

                 Kevin B. Smith
                 Chair, Engineering Acoustics Academic Committee

iii

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

For acoustic frequencies of interest in the development of undersea wireless wide-area networks, wind noise is the dominant contribution to channel noise. The large dynamic range of wind noise forces the network designer to consider wide variations in link margin and effective node-to-node range. Previous reported correlations of acoustic communication performance and wind speed led to multiple hypotheses explaining degradation, including noise variability as well as wind-driven sea-surface effects such as roughness, entrained bubbles, mixing, and stratification. This thesis examines operations of a 40-node wide-area acoustic network in varying noise conditions. This data set is unique in that the environment is strongly downward refracting. Based on theoretical models, wind noise is assumed to dominate all other noise sources. Considerations include dependence of link margin and range on wind speed. Although the experiment was not designed to examine the correlation between transmission range and wind speed, a weak correlation was observed in the limited data set available.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

There are several people whom I must thank, for without them this thesis would not be what it is today.

I would like to begin with my parents, Pat and Blanche, for giving me encouragement and support.

I must give credit to my thesis advisor, Joe Rice, for all the time he has put in guiding me through the whole process.

I thank my co-advisor, CDR Rebecca Stone, who also has given me a great deal of help in understanding the oceanographic aspect of this project, as well as for being very helpful with MATLAB programming.

I would also like to thank several members of SPAWAR San Diego – Paul Baxley, Chris Fletcher, and Bob Creber.

Finally, I have to thank the Combat Systems faculty for teaching me the material I needed to understand and complete this thesis.

THIS PAGE INTENTIONALLY LEFT BLANK

I.   INTRODUCTION

An increasing interest for the United States Navy is the use of underwater communications involving High Frequency (HF – greater than 1 kHz) acoustics. This technology enables the creation of underwater wireless networks. The performance of such a network is dependent on local environment and node geometry. But even for a given environment and geometry, communication performance varies with local wind noise. The working hypothesis is that communications range degrades with increasing wind noise. This thesis attempts to quantify that relationship through the development of a link budget model calibrated with experimentally obtained communications performance data.

In the next chapter, we develop a link budget model as a form of the sonar equation. A link budget is a method used for estimating the signal to noise ratio (SNR) for given parameters such as transmit power, antenna gain, propagation loss, and interference. A theoretical model shows how the link budget changes with varying wind values.

In the third chapter, we describe a relevant experiment. The network design and communication are explained. Information specific to the network is discussed, such as the source level and frequencies used.

In the fourth chapter, we consider the environment and the geometry of the experiment.

The fifth chapter graphically examines how, during the experiment, the wind affected the performance of the network.

In the sixth chapter, we take what was observed in the experiment and re-evaluate the link budget model. This provides us a better understanding of how wind affects network performance.

Finally, the seventh chapter concludes this thesis with a summary and recommendations for future experimentation.

THIS PAGE INTENTIONALLY LEFT BLANK

II.   LINK BUDGET MODEL

A.   SONAR EQUATION

In a standard writing of the sonar equation the left hand side is SE, for signal excess. In developing the sonar equation as a link budget model (rather than detection model), we seek to represent the system's ability to maintain a communications link in a given environment. A complete link budget yields the link margin based on signal processing and other system considerations. In this thesis we limit our development to SNR, expressed as:

$$SNR = PSL - TL - NSL + DI_{rcvr} + DI_{xtr} \qquad (2.1)$$

where

SNR is Signal to Noise Ratio at the receiver

PSL is Pressure Spectrum Level of transmitting platform

TL is Transmission Loss of the medium

NSL is Ambient Noise Spectrum Level of the environment

DI is Directivity Index of the receiver and transmitter.

Each term is in decibels (dB). In this case, the DI terms are zero, because the transmitters and receivers are omni directional. Because of system and channel variation across the operating spectral band, the remaining terms are a function of acoustic frequency, f.

1.   Pressure Spectrum Level

The Pressure Spectrum Level (PSL) represents the density of the transmitted energy across the spectral band of interest. For a transmitted signal composed of tonals,

$$PSL = SL - 10\log_{10}(N) \qquad (2.2)$$

In the calculation, SL is the source level of the wideband transmitted signal, and N is the number of tones instantaneously activated. For this thesis, we consider M-ary Frequency Shift Keying (MFSK) modulation with 128 tones and 1-of-4 keying, or $N=32$. For a Source Level of 179 dB re 1μPa @ 1 meter, the PSL is 164 dB.

2. Transmission Loss

Transmission Loss (*TL*) reduces the sound amplitude as the sound propagates from the source to a receiver. The reference intensity is measured from a point 1 meter from the center of the source. In mathematical terms, *TL* is expressed as[1]:

$$TL = 10\log_{10}\left(\frac{I_0}{I_R}\right)$$ (2.3)

In this case, I_R is the intensity at the receiver, and I_0 is the intensity 1 meter from the acoustic center of the source. Transmission Loss is, in general, due to both geometric spreading and attenuation, which includes loss mechanisms at the surface as well as at the bottom of the sea.

Transmission Loss is dependent on the local environment, acting on sound energy as it propagates along the path from the source to the receiver. *TL* from geometrical spreading is often assumed to correspond to a combination of spherical and cylindrical spreading, and is calculated to as:

$$TL_{Geom} = 10\log_{10}\left(r_t\right) + 10\log_{10}\left(r\right)$$ (2.4)

Where r_t represents the transition range from spherical to cylindrical spreading, and *r* is range, in units of meters.

In Figure 1, the change in the slope is a result of the assumed transition from spherical to cylindrical spreading. In this case, the transition range is assumed to equal the bottom depth of 220m.

---

[1] Urick, Robert, (1983). *Principles of Underwater Sound 3rd. Edition* (McGraw-Hill, Inc., 1983)
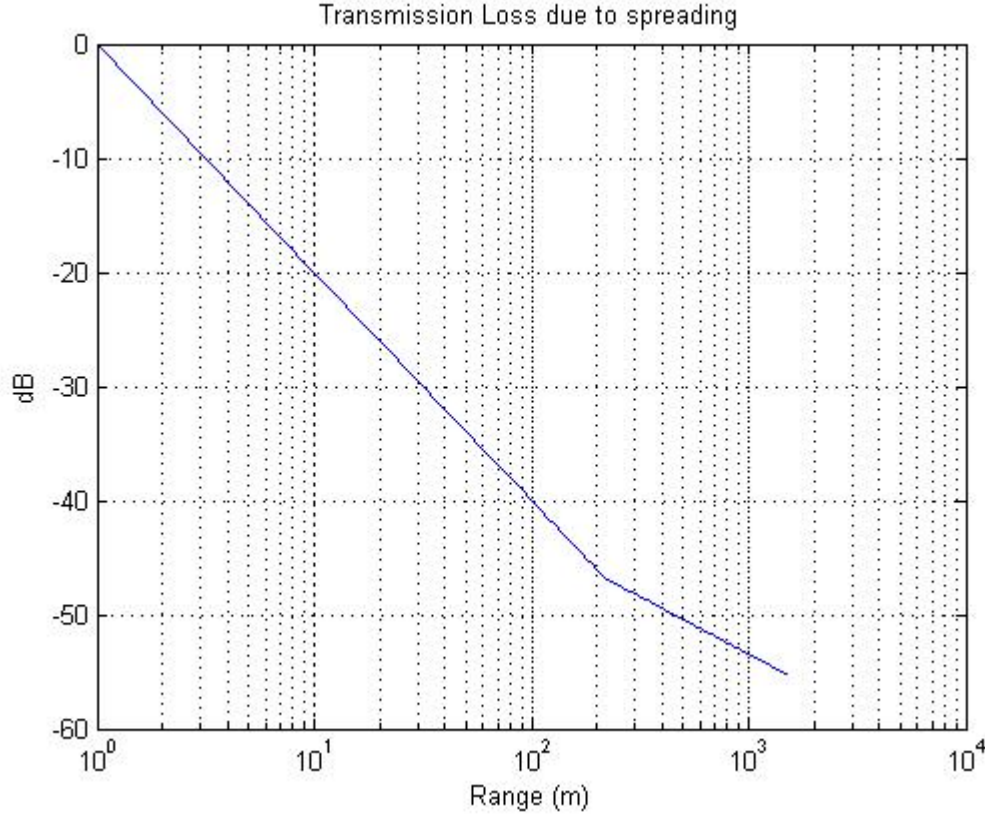
Figure 1. Transmission Loss vs. Range, where range is logarithmic; the transition range is set to 220 m.

Geometrical spreading is not the only component of *TL*. As sound propagates, there is attenuation of the signal due to absorption, scattering, and leakage. There are three effects that contribute to absorption: shear viscosity, ionic relaxation, and relaxation time. *TL* due to absorption varies linearly with range, rather than logarithmically, and can be calculated from[2]:

$$TL_{atten} = \alpha r \times 10^{-3} \tag{2.5}$$

$$\alpha = \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f^2} + 3.0 \times 10^{-4}\left(f^2\right) + 3.3 \times 10^{-3} \tag{2.6}$$

Where *r* is range in meters, α is the attenuation coefficient in dB/km, and *f* is frequency in kHz. This adds linearly with the geometric transmission loss, to give a total *TL* term that

---

[2] Urick, Robert (1983). *Principles of Underwater Sound 3rd. Edition* (McGraw-Hill, Inc., 1983).

5

is dependent upon range and frequency. The effects of scattering and leakage are assumed to be negligible compared to other loss mechanisms.

B.   AMBIENT NOISE

Ambient noise is the background noise of the ocean due to either natural or man-made causes; various sources contribute noise in distinct frequency bands, so that the term varies with frequency. The Noise Spectrum Level (*NSL*) is a measure of the spectral density of the ambient noise in dB.

1.   Wind

Wind speed is thought to affect ambient noise in several ways. First, by simply blowing across the surface of the water, the wind creates flow noise. Also created by the wind are surface waves. When these waves gain large enough amplitude, they make noise by breaking on the surface, creating bubbles of air under the surface, which can oscillate and burst.[3] Wind noise is estimated by[4]:

$$NSL_{wind} = 50 + 7.5\sqrt{w} + 20\log_{10}(f) - 40\log_{10}(f + 0.4) \tag{2.7}$$

where *w* is wind speed in m/s, and *f* is frequency, in kHz.

2.   Precipitation

Rain falling on the surface of the ocean creates sounds by percussion, and the oscillation and collapse of bubbles produced, just as rain falling on a roof during a storm makes noise inside a house. Although there were time periods of our experiment where precipitation occurred, estimates of times and rates were not available, and the effects of precipitation are not included in our study.

3.   Thermal Noise

At high frequencies the noise spectrum is dominated by noise arising from the random motion of water molecules. The contribution to the noise spectrum from thermal noise, *NSL_{thermal}* can be calculated from[5]:

---

[3] Urick, Robert (1979) *Sound Propagation in the Sea* (Defense Advanced Research Projects Agency 1979).

[4] Wenz, G.M. (1962). "Acoustic Ambient Noise in the Ocean: Spectra and Sources" *Journal of the Acoustical Society of America*, 34,1.

[5] Urick, Robert (1983). *Principles of Underwater Sound 3rd. Edition* (McGraw-Hill, Inc., 1983).

$$NSL_{Thermal} = -15 + 20\log_{10}(f) \tag{2.8}$$

where f is frequency in kHz.

4.   Shipping

Shipping traffic on the open ocean creates a substantial amount of noise underwater, from components such as propellers, engines, and flow. This noise can be detected over very large distances. The contribution from each individual ship may not have a large affect on Noise Level; however, when it is considered that there are thousands of tons of shipping crossing the Pacific Ocean at any time, this is a significant source of noise. Accuracy of estimates of shipping noise are limited by the fact that shipping density and ship mechanics have changed in the decades since original estimates were made, and vary locally as well. However, it tends to be below the frequencies of interest for communication, making it less important for our example. Urick gives the following expression for the ambient noise due to shipping. In this expression D is the density of shipping traffic, from 0 to 1; 0 being no traffic, and 1 being maximum traffic[6].

$$NSL_{Shipping} = 40 + 20(D - 0.5) + 26\log_{10}(f) - 60\log_{10}(f + 0.03) \tag{2.9}$$

where f is frequency in kHz.

5.   Biologics

The animals that live under the surface also create noise. The snapping of shrimp, calls of whales, and whistles of dolphins are just some of the sounds that are commonplace, all contributing to the ambient noise levels. For this analysis, we neglect biological noise, as it tends to be outside the frequency range of interest to this study.

C.   AMBIENT NOISE VS. WIND

All of ambient noise components for which spectral level estimates were available are combined into the total *NSL* and plotted in Figure 2. Clearly, in the frequencies of interest to our study wind noise should dominate the total noise.

---

[6] Urick, Robert (1986) *Ambient Noise in the Sea* (Peninsula Publishing Los Altos, CA 1986).
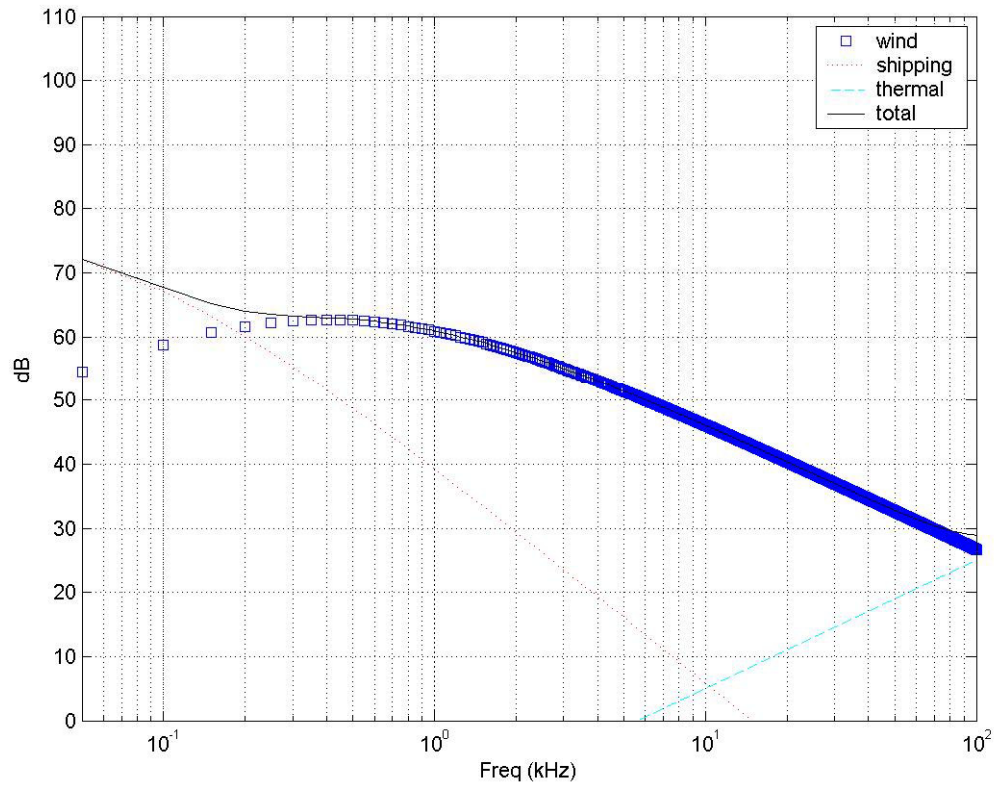
Figure 2.   Noise Spectrum Level curves using theoretical equations; in the HF band, wind noise (wind speed 5 m/s, and shipping is medium) is dominant.

Figure 3 describes the variability of the ambient Noise Spectrum Level for changing wind speeds. Notice that for HF signals, there is a large dynamic range of more than 30 dB. This further indicates the importance of wind noise in calculating ambient Noise Spectrum Levels and SNR.
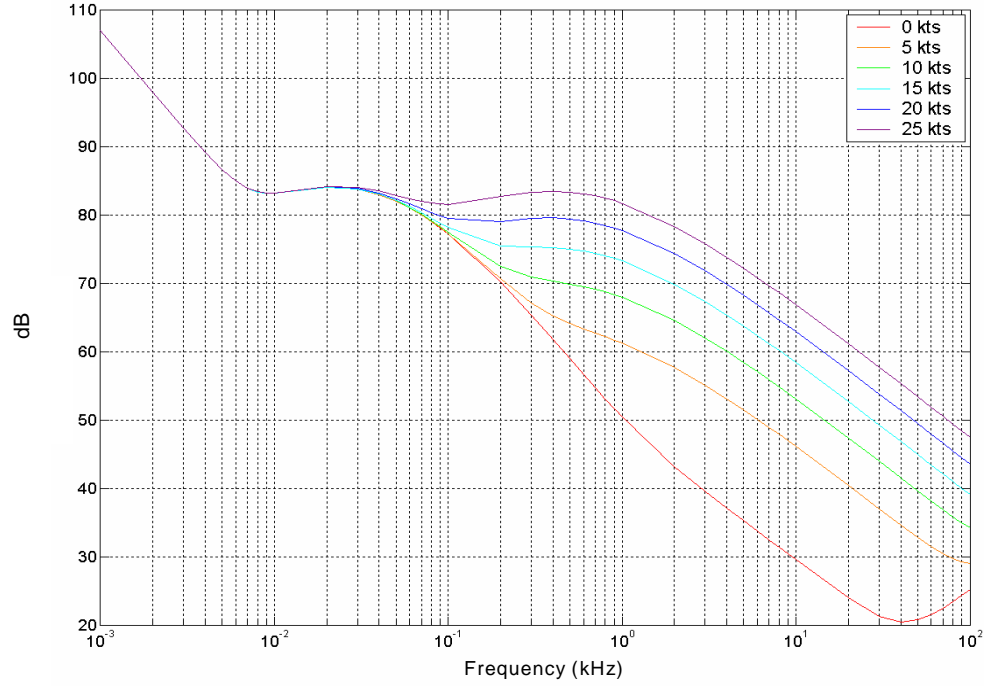
Figure 3. Dependence of ambient Noise Spectral Level upon wind speed; note the variance in the High Frequency band (greater than 1 kHz) (dB re 1 μPa).

D. SNR VS. WIND

Let us now examine the influence of wind on SNR. Revisiting the sonar equation gives:

$$SNR_{Channel} = PSL - TL - NSL , \qquad (2.10)$$

where the term (–*TL-NSL*) represents the environmental factor which needs to be overcome by the source PSL in order to obtain the SNR necessary to achieve desired communication rates. For this study Transmission Loss was assumed to be given by geometrical spreading (equation 2.4) with the transition range equal to 220m. Attenuation due to absorption was calculated using equation 2.5 and 2.6. The shipping level was assumed to be medium, and the sea state is calm. Only the wind speed is varied, from 0 to 25 m/s in 5 m/s increments. Figure 4 shows this environmental factor for those six different wind conditions.   Notice that although the largest impact of *NSL_wind* is in the highest frequencies, the largest amount of variability in the impact of the wind noise is around 20 kHz, presumably because of the competing factors of wind noise and absorption. Wind noise decreases with frequency while absorption increases. This

9

effect is clearly seen in the Shannon water pouring theorem, where for increasing ambient noise and constant Transmission Loss, a continually greater *SNR* is required for signal reception.[7]

---

[7] Shannon, C.E., Weaver, W. (1949) *A Mathematical Theory of Communication* (Univ. of Illinois Press, Urbana, IL. 1949).
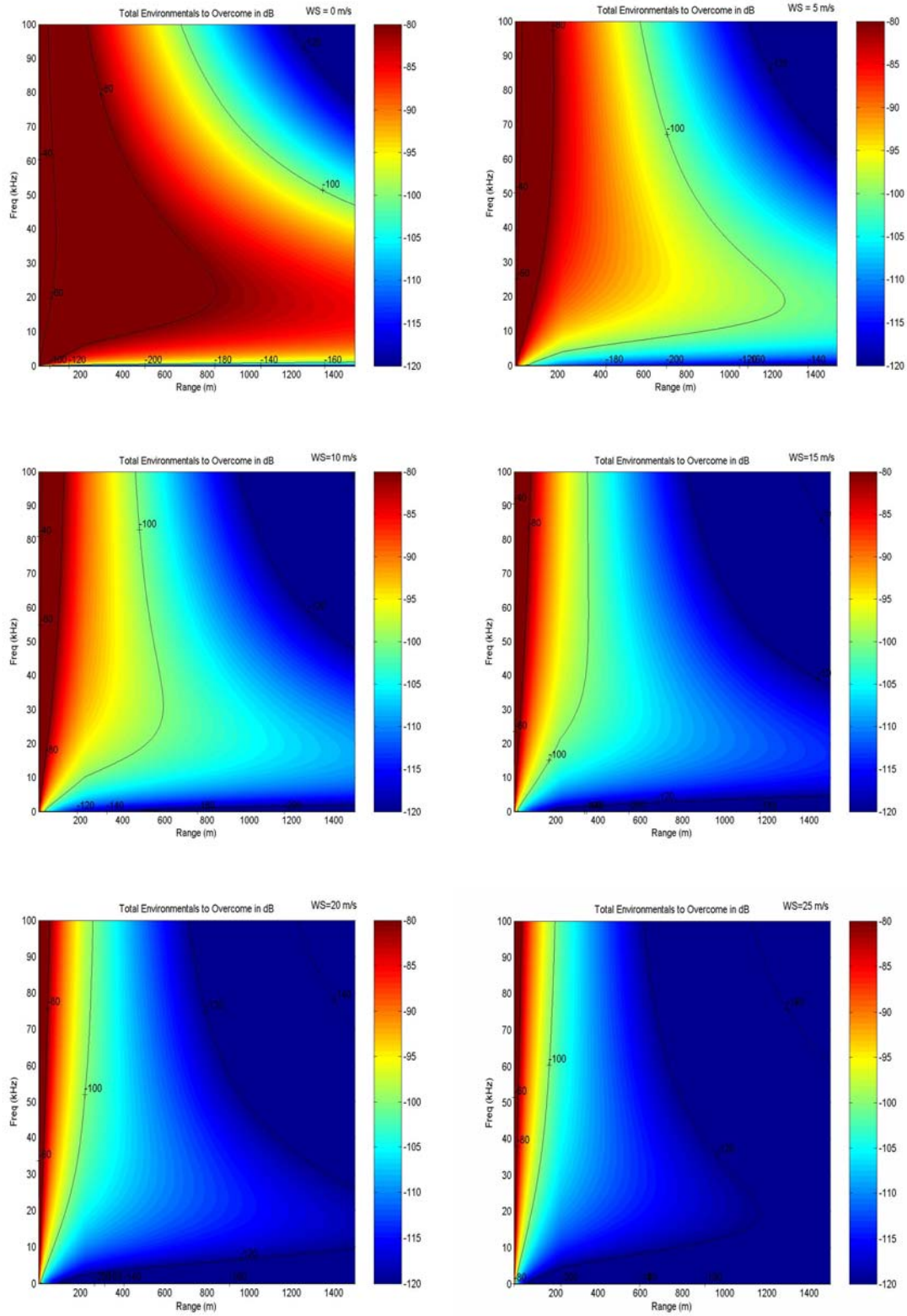
Figure 4.   Environmental factor degrading channel Signal to Noise ratio for wind speeds ranging from 0 m/s to 25 m/s; variability due to wind noise is readily apparent.

THIS PAGE INTENTIONALLY LEFT BLANK

III.   EXPERIMENT

Our experiment used a 40 node network deployed on the bottom of the ocean. To connect to the surface and send communications, a gateway buoy was moored at the southern end of the seafloor grid, as seen in Figure 5.
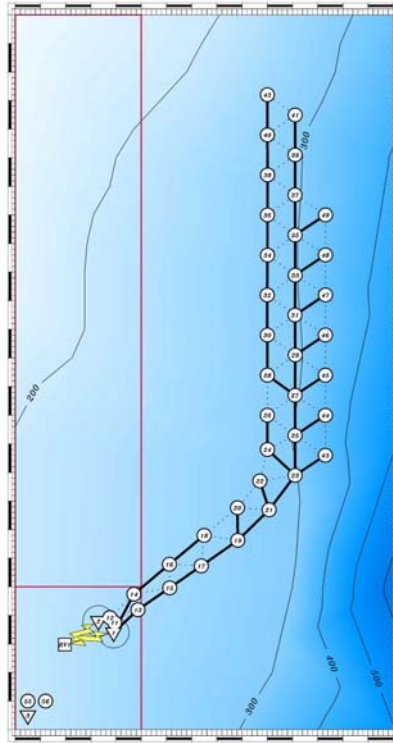

Figure 5.   The deployed network at COMEX; each circle represents one node, and the triangles represent gateway buoys. Each node is separated by 1-3 km (.5-2 nm).

This experiment was not purposefully designed to measure the performance of the underwater network with respect to wind. Therefore many measurements which would have helped to establish a firm relationship between range and wind speed such as measured ambient noise levels were not obtained. The gateway buoy recorded all network traffic that it could hear both migrating towards and away from it. That is, it recorded all message traffic, not just those messages that were addressed specifically to the gateway. Network performance was quantified by range to the furthest node each message could be heard traveling and decoded as it traveled away from or toward the gateway. The node number where the acoustic signal was last overheard was recorded,

and used to find the range value using Table 1. Because of this, the ranges are discrete values, rather than having continuous range measurements. In short, the gateway buoy was the receiver, and all ranges were measured from there to the furthest transmitting node.

Node	Range in km	Range in nm
12	0.76	0.4
13	1.85	1
14	2.6	1.4
15	4.4	2.4
16	5.6	3
17	7.0	3.8
18	8.5	4.6
19	10.0	5.4
20	11.1	6
21	13.0	7
22	13.7	7.4
23	14.0	8.2
24	15.5	8.4

Table 1.   Ranges to each node.

A.   MODEMS

For this experiment, Benthos acoustic modems were used in each network node, as well as in the gateway buoy. To pass a message between nodes, the sending node first transmits a Request to Send (RTS) packet. The receiving node responds with a Clear to Send (CTS) packet. When that is received, the sending node transmits the data of the message in concatenated 256 byte sub-packets. If any of these packets are corrupted, the

14

receiving node sends a Selective Repeat Request (SRQ) packet specifying which data sub-packet must be resent.
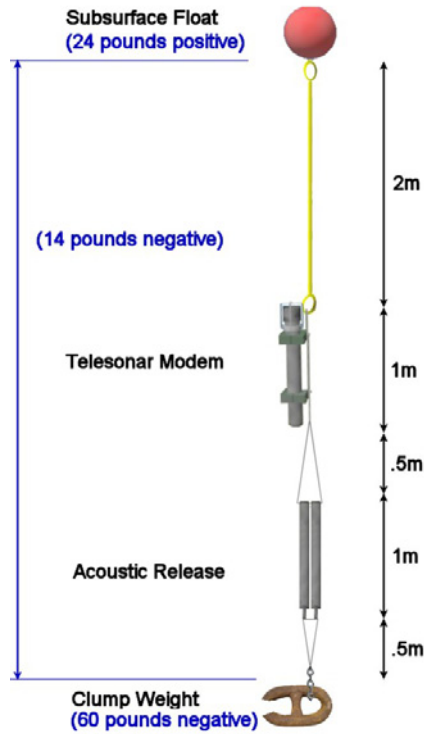
Figure 6.   A schematic of one node, including the acoustic modem.[8]

B.   SOURCE LEVEL AND FREQUENCIES

The source level of each acoustic modem was set to 179 dB, and used 128 tones for 1-of-4 MFSK. Each operated in the frequency band of 9-14 kHz.

C.   DATA

The data were passed through the network in one of two types of packets: data and utility.

Type of Packet	Utility	Data
Raw Bit Rate	2400 bps	2400 bps
Information Bit Rate	150 bps	800 bps
Packet Size	9 bytes	Variable

[8] Rice, Joseph A. *Seaweb Acoustic Communication and Navigation Networks* from Proceedings of the International Conference "Underwater Acoustic Measurements: Technology and Results" Heraklion, Crete, Greece 28th June-1st July 2005.

Number of Packets	656	463

Table 2.   Comparison between Utility and Data Packets during experiment.

1.   Utility Packets

Utility packets are transmitted at a bit rate of 150 b/s. Though both packet types have the same raw bit rate, the information bit rate of utility packets is slower because of additional coding. Theoretically, utility packets should be more reliable at longer ranges because of the larger amount of error correction and redundancy encoded within their data. Their size is quite small at 9 bytes. They are used for network maintenance messages, for instance, Clear to Send or Request to Send packets. The utility packets were used much more frequently during the experiment, providing us more data points.

2.   Data Packets

Data Packets are used for actual data being sent through the network. These are larger in size at approximately 256 bytes, and are sent at 800 b/s. These typically contained 4 lines of text messaging.

IV. EXPERIMENT ENVIRONMENTAL FACTORS

A. GEOMETRY

The depth of the ocean at the gateway buoy was approximately 220 meters, gradually increasing with range away from the buoy mooring. The nodes did not rest on the ocean bottom, but floated 3 meters above. Additionally, the modem transducer on the gateway buoy was not at the surface; it hung 30-40 meters below. The distance between the gateway node and the nodes of interest in the grid ranged from approximately 2 to 16 km.

To best approximate Transmission Loss, the unique bathymetry of the experiment should be modeled. Additionally, the local environment and sound speed profile should be represented in this model.

B. SOUND SPEED PROFILE

The sound speed profile of the ocean was not constant at the network, but varied throughout the course of the experiment as seen in Figure 7. The experimental sound speed profiles were taken using Conductivity, Temperature, and Depth (CTD) sensors and Expendable Bathythermograph (XBT) measurement devices, by members of the Naval Oceanographic Office.
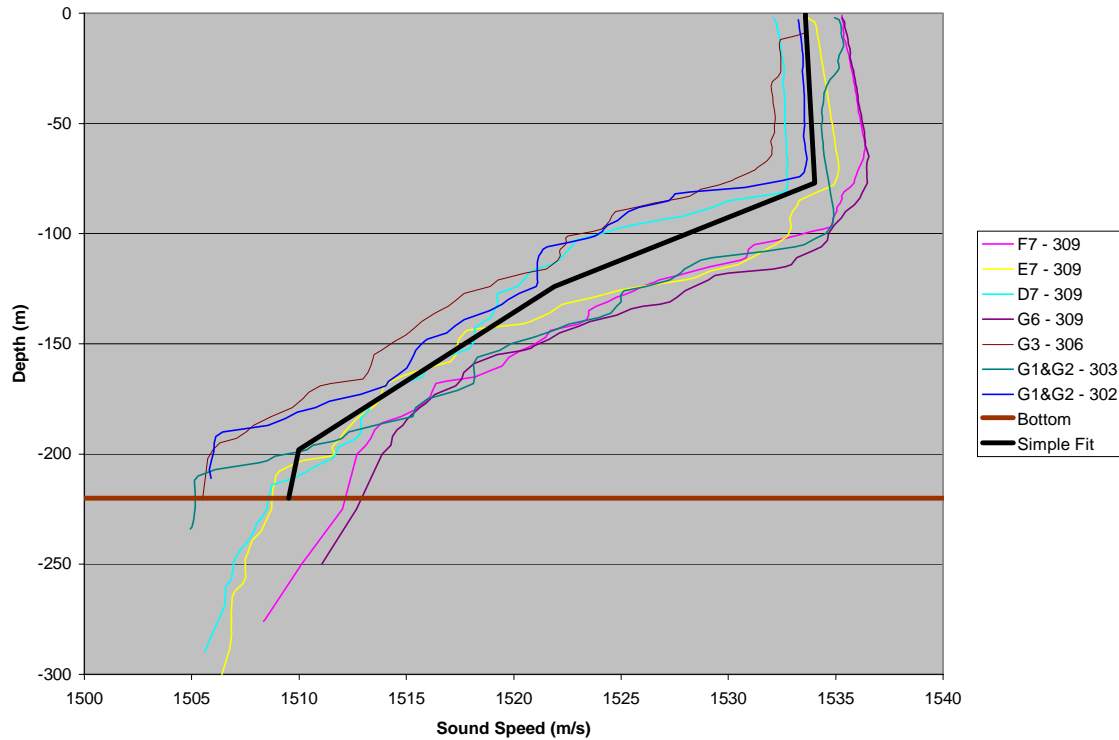
Figure 7.   Combined SSP during the course of the experiment.

A characteristic sound speed profile from the experiment is included in Figure 8. Sound arcs toward the slower sound speed rather than traveling in a straight line. Notice the slight upward refraction in the mixed layer, extending to approximately 75 m. The mixed layer depth was not constant throughout the experiment. The main difference was the raising and lowering of the thermocline (the region of strong gradient just below the mixed layer). The change in the depth of the mixed layer was as much as 50 m. The region below the mixed layer was a downward refracting environment.
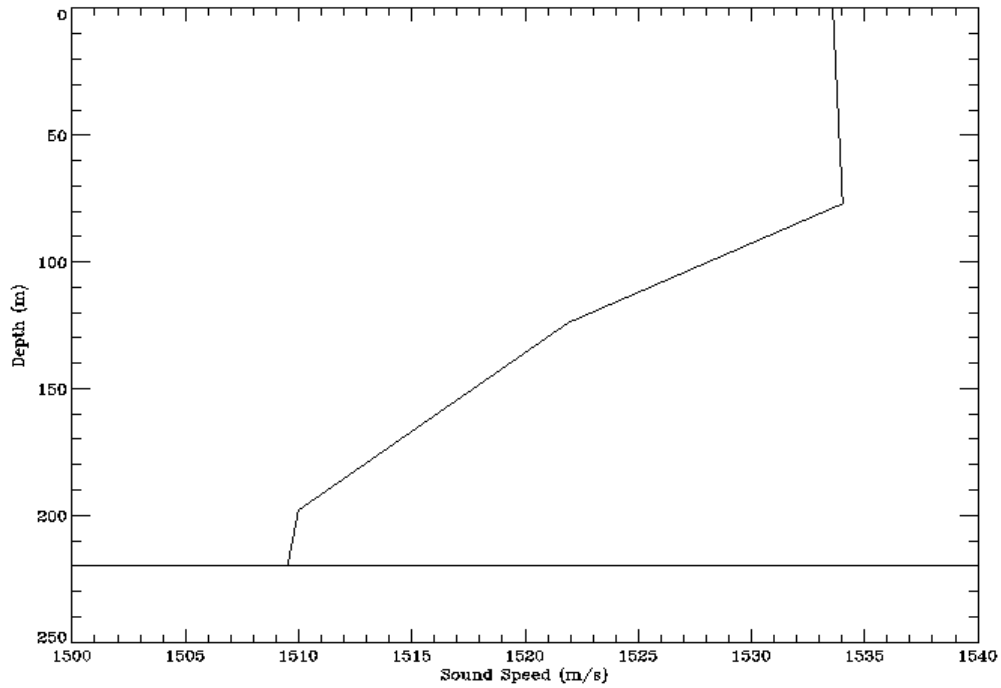
Figure 8.   A simplified sound speed profile during the experiment, compiled from approximately 10 separate SSPs, courtesy of Paul Baxley, SPAWAR San Diego.

C.   TRANSMISSION LOSS VS. RANGE

The best method of approximating Transmission Loss is in a physics based model which takes into consideration bathymetry, sound speed profiles, surface roughness, and bottom type. There are several options available; however, a range-independent Kraken model is used. This is a normal mode propagation model. The assumptions are that the bottom is flat, the source depth is 217 m, the receiver depth is 50 m, the frequency is 11.5 kHz (midway between 9 and 14 kHz), and the sound speed profile is that given in Figure 8. The modeling was done by Paul Baxley of SSC San Diego. Five cases are modeled, each with different assumptions about the boundary conditions of the ocean channel. *TL* vs. range is plotted for each case in Figures 9-12. In each figure, the dashed line is the plot of purely geometric *TL*, due to a combination of spherical and cylindrical spreading as shown in Figure 1. Figure 9 shows the *TL* calculated from the Kraken model without surface or bottom losses. Note that at very short ranges the model predicts considerably

19

higher transmission losses than the simplified geometrical *TL*. At longer ranges the model also shows greater losses. At least part of this discrepancy can be explained by the fact that the Kraken model includes losses due to absorption.
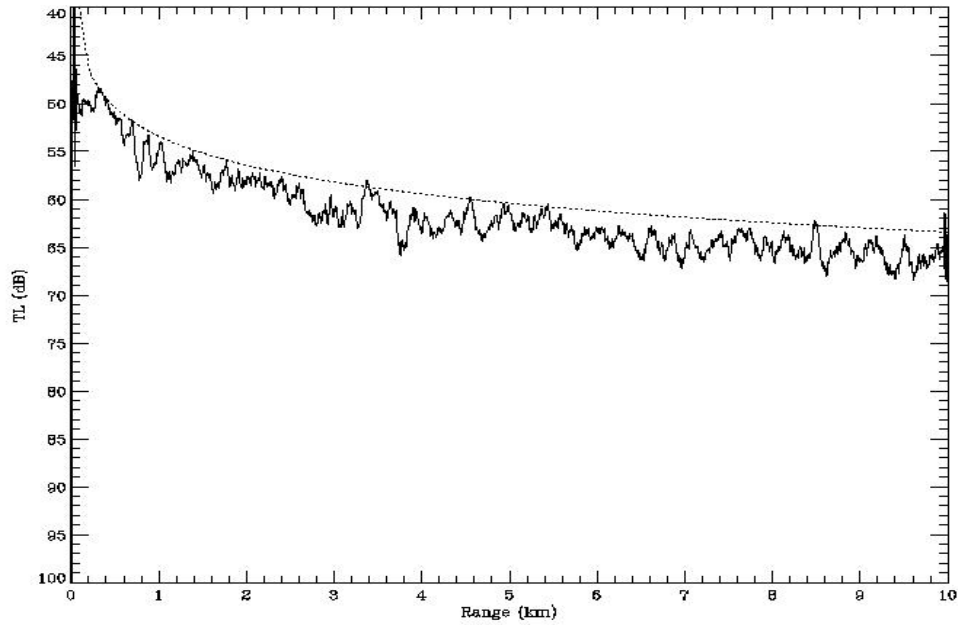

Figure 9.   Kraken Model of Transmission Loss vs. Range, with no surface or bottom losses.
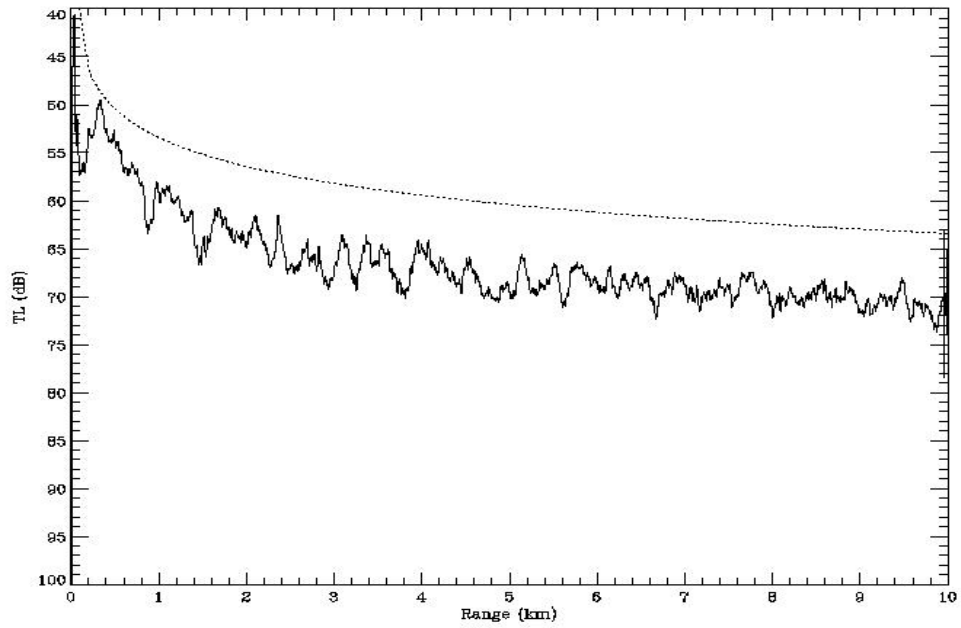
Figure 10.   Kraken model of Transmission Loss vs. Range for a lossy bottom and loss
of 3 dB/bounce from surface reflection.
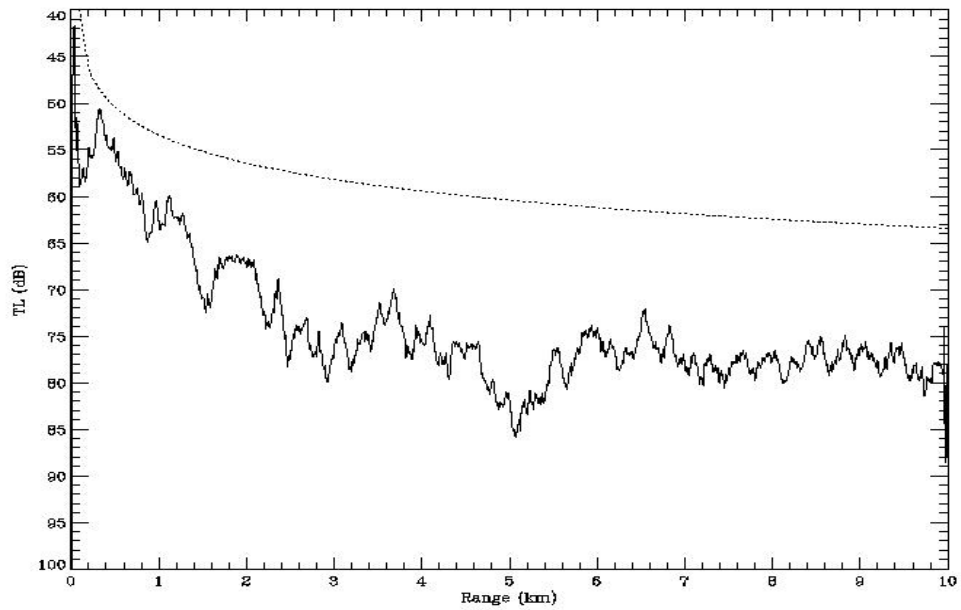
Figure 11.   Kraken model of TL vs. range for a lossy bottom and loss of 6 dB/bounce
from surface reflection.
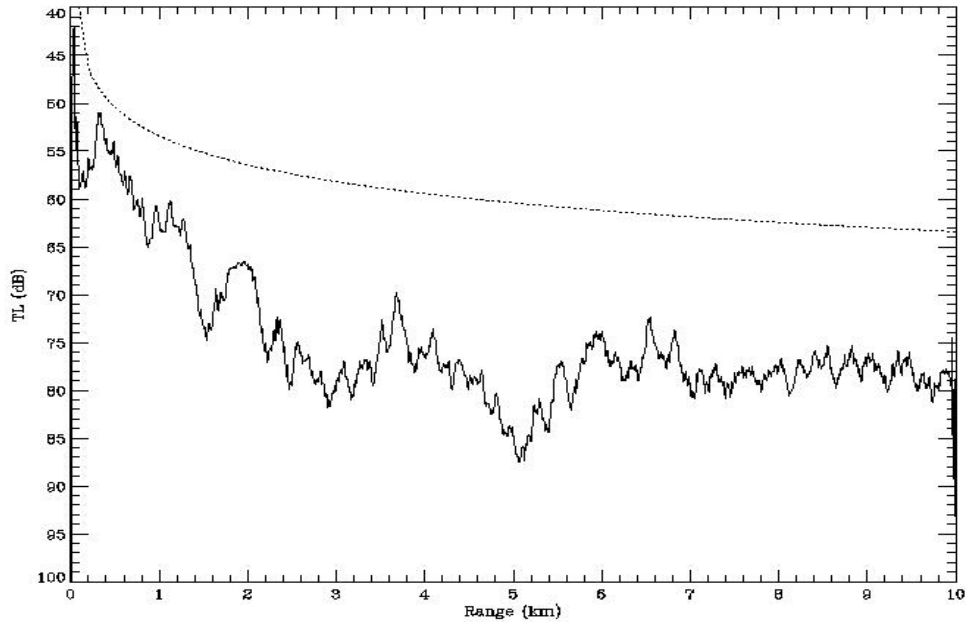
Figure 12. Kraken model of TL vs. range for a lossy bottom and loss of 9 dB/bounce from surface reflection.

Figure 10 shows a difference of almost 10 dB greater *TL* when surface and bottom losses are introduced. As expected, Figure 11 shows even greater losses when the surface loss is 6 dB per bounce, which corresponds to four times the power loss for each bounce than for no surface losses at all. Finally, Figure 12 displays even worse conditions, with a lossy bottom and 9 dB loss per surface bounce. Using the Kraken model for different losses demonstrates the variability in *TL* for more complicated models rather than when using a simplified model such as geometric spreading. It also shows that the TL could be considerably higher than that calculated from simple geometrical spreading with absorption.

D.   RAY TRACING

This was a downward refracting environment. Using sound speed profiles and local environment bathymetry, we can create the chart of possible ray paths from the seafloor transmitter (network nodes) into the ocean and eventually to the receiver (gateway buoy) displayed in Figure 13.
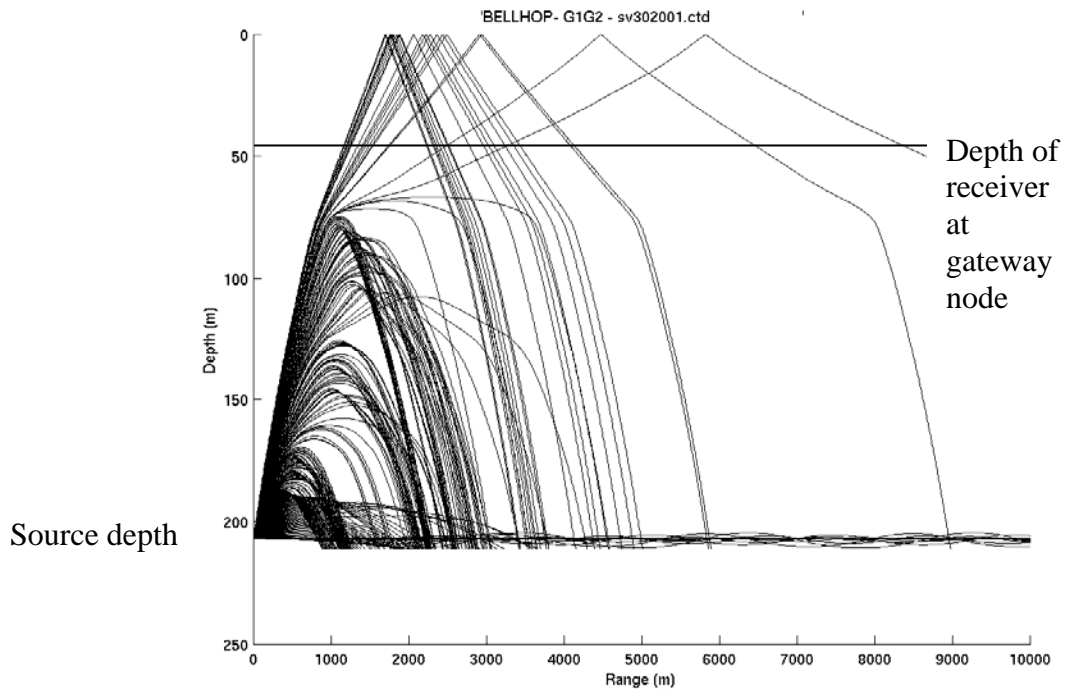
Figure 13.   Ray traces for sound speed profile taken near the gateway buoy. The
gateway buoy transducer depth was approximately 30-40 m, and bottom bounce
rays are excluded.

THIS PAGE INTENTIONALLY LEFT BLANK

V. EXPERIMENTAL WIND SPEEDS AND COMMUNCATION RANGES

A. WIND VS. TIME

Two sets of wind speed vs. time data are examined for this experiment. The first was forecast wind data, from COAMPS™ WESTPAC 27 km operational model run, provided by the Fleet Numerical Meteorology and Oceanography Center. This was the most complete data set, with a value for wind speed at every hour. Each forecast was based on an analysis performed at 0000Z or 1200Z. For the purposes of this study, we were not able to determine if reports from ships in that area were incorporated in these analyses. However, these data do not agree well with the observed wind speed from the research vessel (RV, which was moored at the site of the network) during the experiment period. The other set of wind speed data is from the RV Bridge. The bridge data were recorded three times a day, each day. Figure 14 shows the wind data during the period of the experiment.
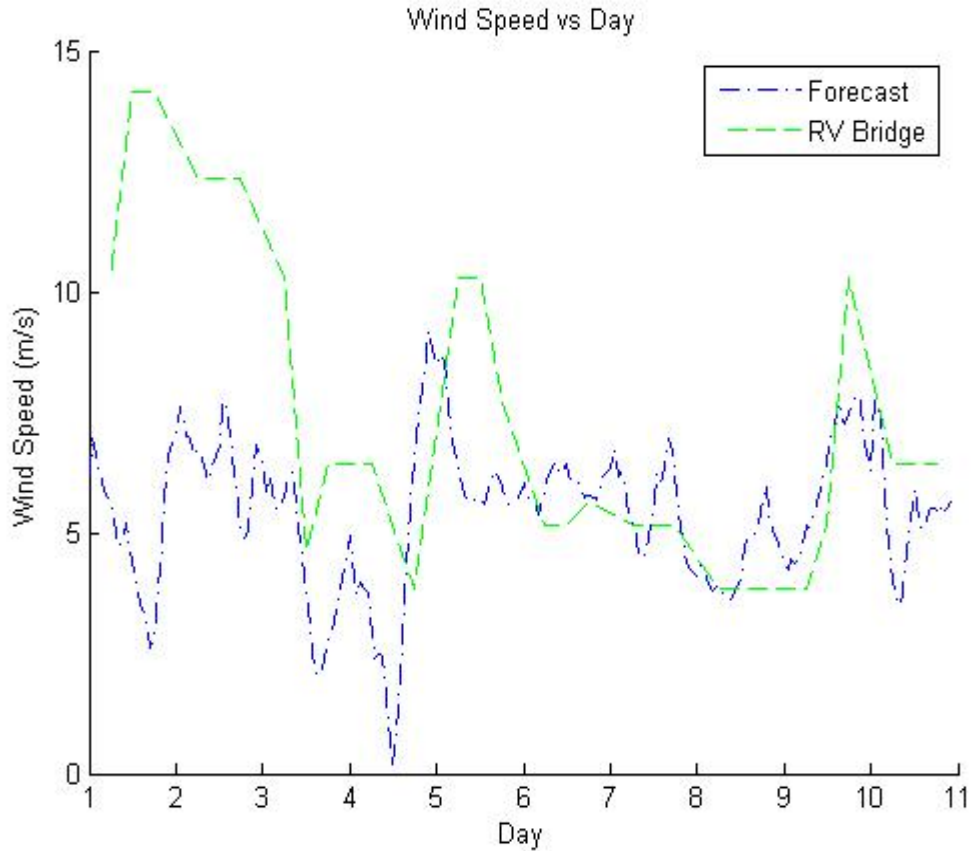
Figure 14.   Wind speed vs. time for all three measurements of wind data. The variability in wind speed over the course of the experiment provides the basis for this experiment.

B.   RANGE VS. TIME

As stated previously, the measured communications ranges are discrete values, based on the distance to the furthest node heard during the sending of network packets. The gateway buoy recorded the nodes that were communicating, and the time at which it took place. The ranges corresponding to only the most distant overheard node are plotted against time to show network performance as the experiment continued. The communication from all closer nodes was ignored when plotting range, and all nodes are assumed to be communicating at an equal rate. However, since the undersea network was not in continuous use there are breaks in time where no traffic is observed. The following figure shows utility packet range vs. time.
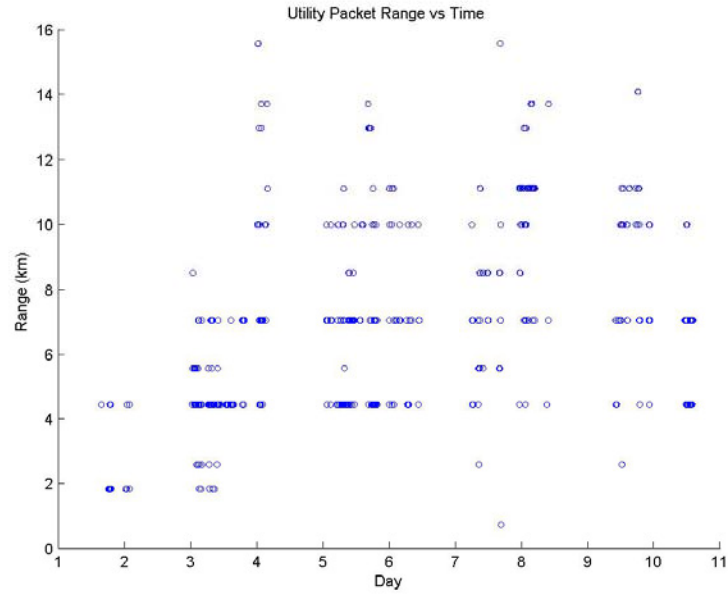
Figure 15.   Utility Packet Range vs. Time
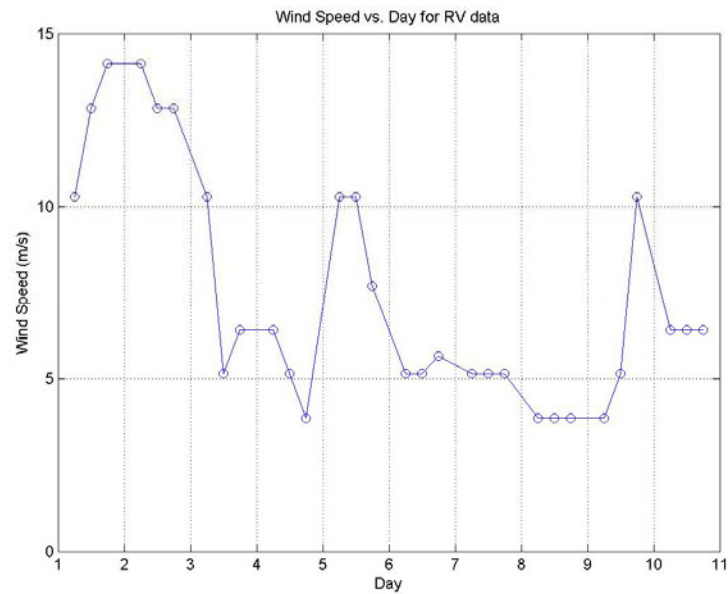
Figure 16.   RV wind speed vs. time plot, for comparison to range vs. time

However, there are ambiguous data in Figure 15. Since not all messages were destined for the farthest node, it is possible that some of the transmissions which are plotted as if they represent the farthest range attainable are actually terminating at the message destination, and not the limit of the gateway buoy acoustic range. If a message was addressed to a node at a range less than the maximum range the gateway could listen,

27

then it would stop before the limit of the gateway hearing was reached. That is, the data are incorrect because the maximum distance over which that signal was heard is shorter than it would have been if the packet had been destined for a more distant node. Culling those ambiguous data was not performed. The average range for utility packets was 6.77 km, and the maximum range was 15.7 km.
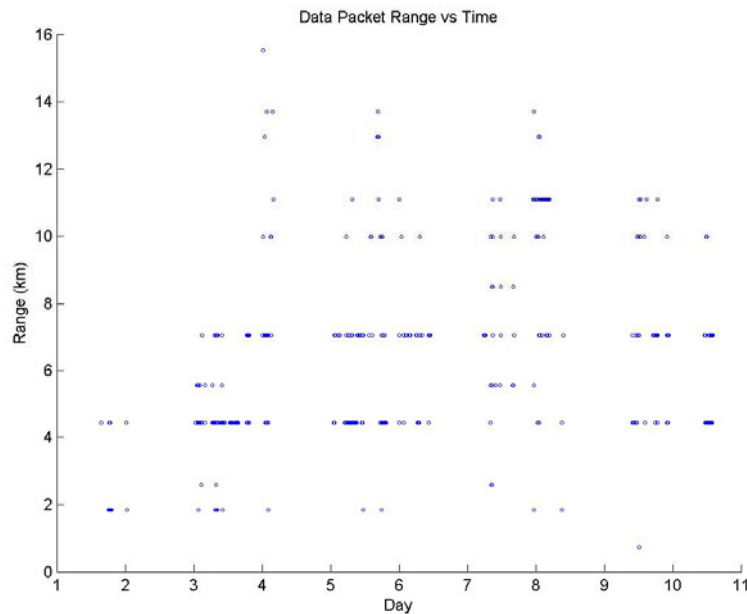

Figure 17.   The plot of Data packet range vs. time shows network performance.
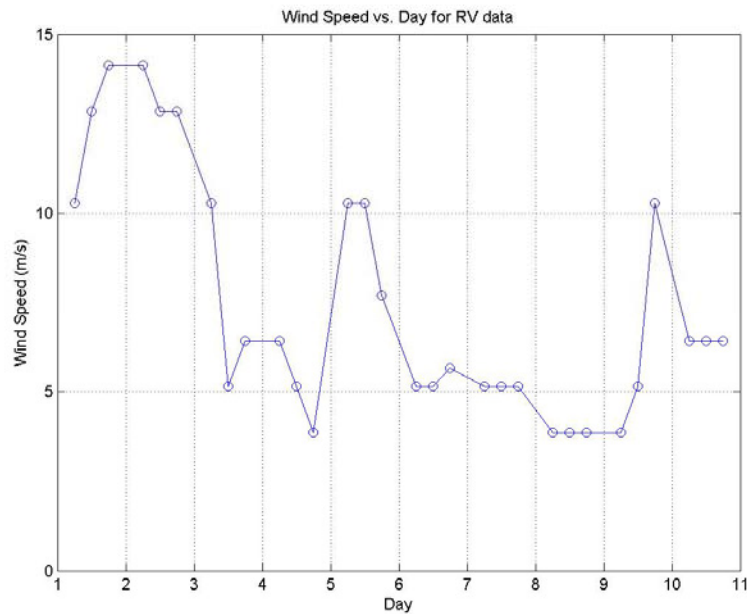
Figure 18.   RV wind speed vs. time for comparison to range vs. time

28

The data packet range and time plot is created in the same manner as the utility packet range vs. time plot, and has the same ambiguous data. For data packets, the average range was 6.33 km and the maximum range was 15.7 km, as well.

C. RANGE VS. WIND SPEED

Because there are far fewer wind speed vs. time data points than range vs. time, there is poor resolution in plotting wind and range against each other. Range was assigned a corresponding wind speed value for the wind speed observed prior to the time that each range was taken. This is then plotted with range as a function of wind speed, in Figure 19.
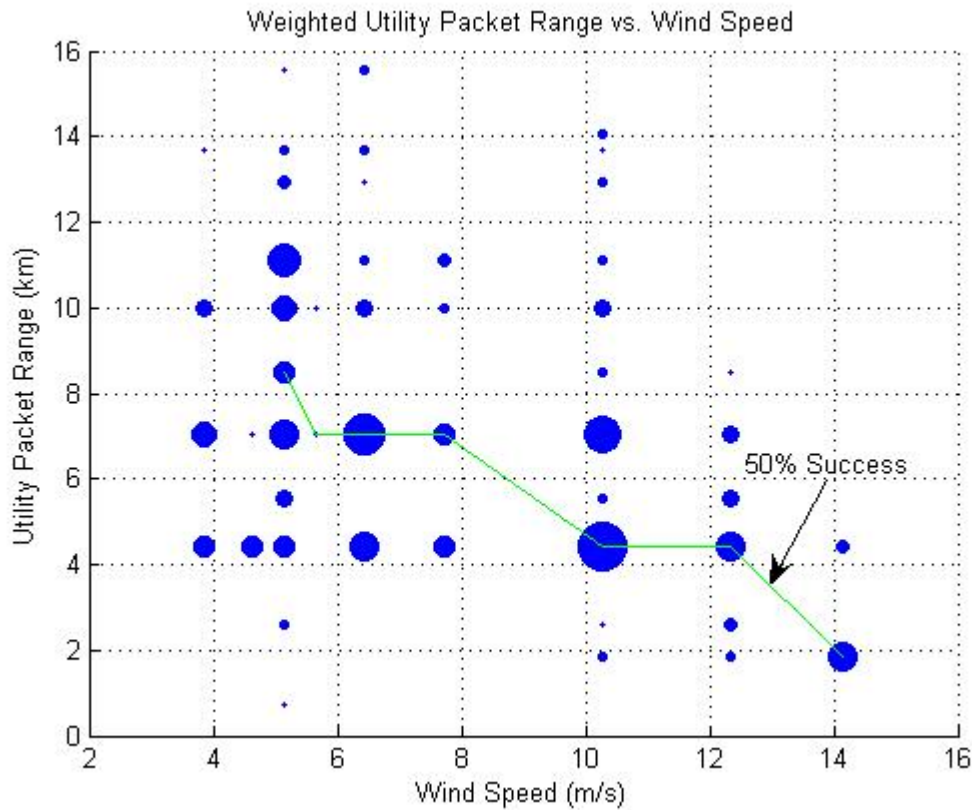
Figure 19.   Weighted utility packet range vs. wind speed, with a 50% line using RV wind data.

The plot of utility packet range and wind speed is weighted to show how often a particular range happened for a given wind speed. A larger circle denotes greater occurrence. The total number of all utility packets overheard at each wind speed was recorded. The 50% success line in Figures 19-22 represents the node for which half of all

utility packets were overheard either at or further than that node. For example, when the wind speed was 14m/s, half of the utility packets overheard originated from the node about 2km away or from more distant nodes. Wind data for Figures 19 and 21 were observed at the RV Bridge, while the wind data for Figures 20 and 22 are from forecast data. Using the forecast wind data, a weighted occurrence plot of range and wind speed appears slightly different. The same processing is applied to the data packet ranges.
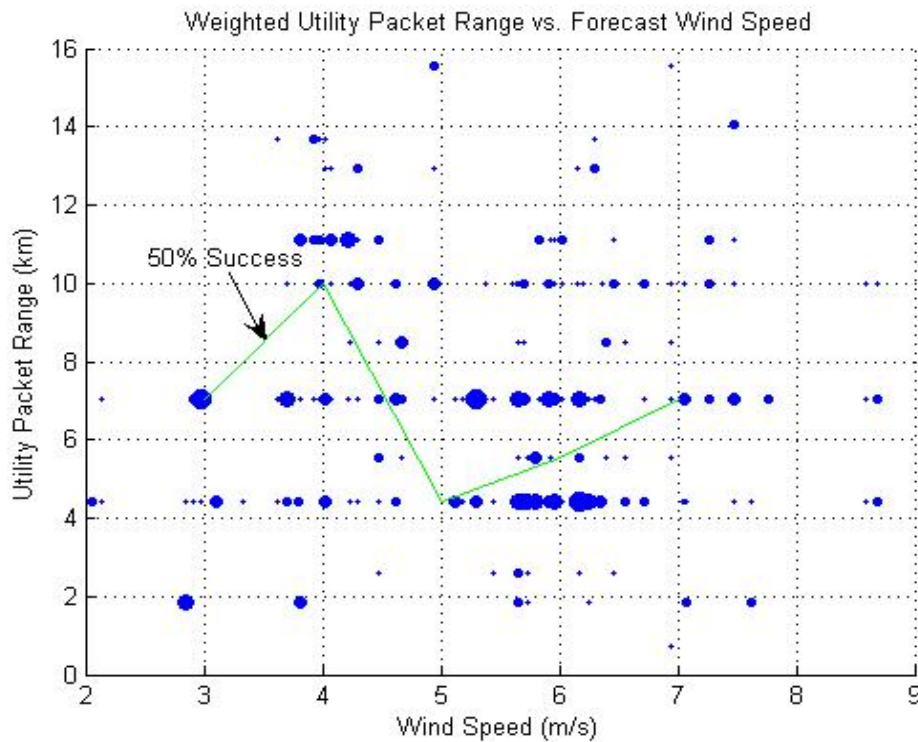
Figure 20.   Weighting the forecast wind speed vs. range shows a less organized plot, with less clear potential trends.
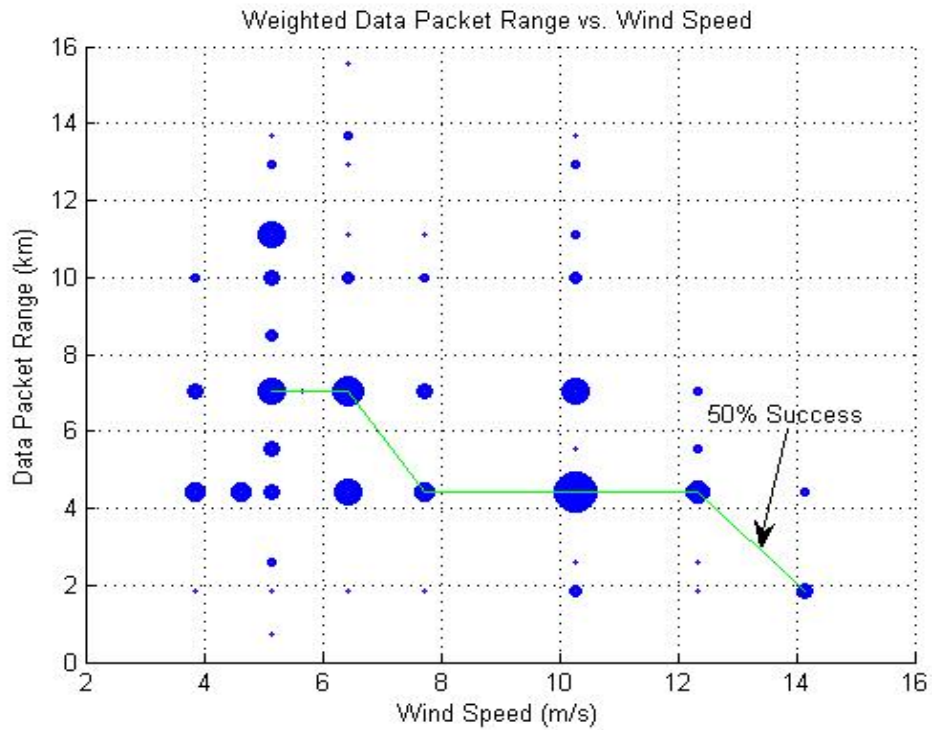
Figure 21.   Weighted data packet range vs. wind speed for RV wind data. Larger
circles are for more occurrences, and 50% success lines drawn.
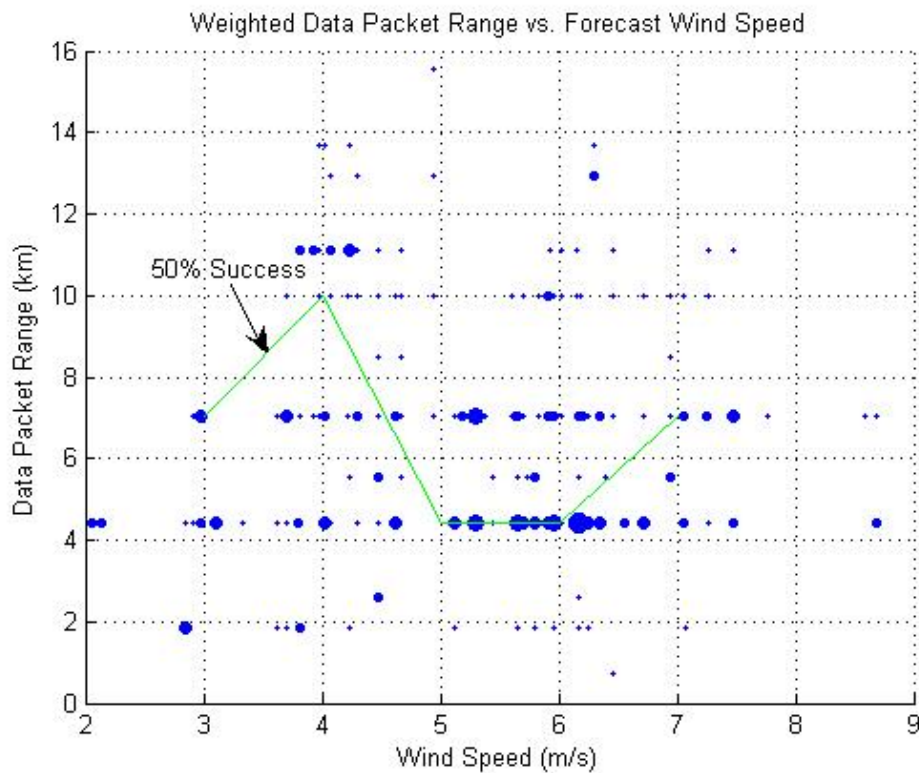
Figure 22.   Weighted data packet range vs. forecast wind speed; again, the trends
between RV and forecast data differ.

31

THIS PAGE INTENTIONALLY LEFT BLANK

VI. EXPERIMENTAL LINK BUDGET

Using the information that has been experimentally collected, we now revisit the link budget to create a new relationship between range and wind speed. Solving Equation 2.1 for *TL* yields:

$$TL = PSL - NSL - SNR \qquad (6.1)$$

The only term dependent on range is *TL*. Assuming *NSL* is dominated by wind noise, range is now determinable for any known wind speed. However, the relationship involves a transcendental equation, since:

$$TL = 10\log_{10}(r_t) + 10\log_{10}(r) + \alpha r \qquad (6.2)$$

Substituting equation 6.2 into 6.1 gives:

$$10\log_{10}(r) + \alpha r = PSL - NSL - SNR - 10\log_{10}(r_t) \qquad (6.3)$$

Returning to chapter 2 and using the relationship for *NSL_wind* in equation 6.3 gives:

$$10\log_{10}(r) + \alpha r = PSL - SNR - 10\log_{10}(r_t) - (7.5\sqrt{w} + C) \qquad (6.4)$$

where *C* is a constant for a given frequency. Thus we have a relationship for wind speed and range; however range cannot be found explicitly, save for at shorter ranges when absorption can be ignored. (For signals at our center frequency, 11.5kHz, the loss from absorption is calculated as 1.3dB/km.) Solving for the range in that case yields:

$$r = 10^{\frac{\left(-7.5\sqrt{w} + PSL - SNR - 10\log_{10}(r_t) - C\right)}{10}} \qquad (6.5)$$

Admittedly, this simplified model does not reflect the complete dependence of the communication range on wind speed since Transmission Loss will also dependent upon wind due to increased surface scattering losses. Over short ranges, however, the losses due to surface bounces are expected to be small in comparison to geometrical spreading and absorption.

We can see from this simplified model that the expected communication range decreases with increasing wind speed. The limited data set available supports this

relationship. With a new and better data set, it may be possible to establish a more definitive relationship for network performance prediction based upon wind speed.

VII. CONCLUSIONS

This thesis intended to examine the correlation between communications range and wind speed. To achieve this, we created an example link budget as a benchmark for hypothetical network performance, and showed that theoretically, increased wind speed degrades network performance. Next, we examined experiment data and used range vs. wind speed plots to quantify communications range against wind speed. Finally, we revisited the link budget, and used the experimental data to show the degradation of network performance for increasing wind speeds. Unfortunately, this experiment was not intended to test this hypothesis in a controlled and statistically significant manner, and our result therefore cannot be considered conclusive.

Although the data show a rough correlation between wind speed and communications range, a more exact relationship between the wind speed and range could not be established. A controlled experiment should be carried out to obtain more conclusive data. That experiment should have several improvements over the last. First, wind speed and sea conditions must be sampled with rigor. Repeated sound speed profile measurements should be taken to resolve any periodic changes of the mixed layer and thermocline. Making sure that many messages are sent within the network for each wind speed is a must. This will create many more data points for analysis. Ambient noise should be measured in both the mixed layer and in the thermocline. Finally, a directional receiver for measuring vertical arrival angles to verify the ray paths would be helpful in better understanding the multipath structure. Some things should be retained from the earlier experiment. The fact that the network stretched well beyond the hearing of the gateway buoy allowed for data to be recorded with no fear of acoustic signals propagating beyond the network while within hearing of the gateway buoy. Also, a time of year where significant wind speed changes are the norm is a must, to ensure a wide range of wind speeds.

Using a calibrated link budget model is a useful tool for network design. It allows for simple network deployment no matter what the conditions or local environment. In order for the Department of Defense to exploit acoustic communications technology, more research is necessary.

APPENDIX: MATLAB CODE

A.   MAIN LINK BUDGET PROGRAM

```
%Link Budget Equation
%Thesis Version 3
clear all; clc; close all;
%**********************
%initialize parameters
[f, R, depth, ws, D] = initialize;


%***************************
% Transmission Loss (TL)
disp('calculating TL')
[TL, TLa, TLs, alpha1] = transmissionloss(R, f, depth);


%*****************************
% Noise Level (NL)
disp('calculating NL')
[NLwind, NLship, NLturb, NLtherm, NLtotal, NL] = noiselevel(R, f, ws, D);
%*************************************
%Source Level
disp('caluclating source level');
[SL] = sourcelevel(R, f);
%************************************
%Link Margin
disp('calculating the link margin')
linkmargin = SL + TL + NL;
%************************************
%Calculate the 'Noise' to be overcome
disp('calculating the Noise to be overcome')
relSNR = NL + TL;
```

```matlab
%**************************************
%PLOT OUTPUTS
%***************************
disp('generating plots')
%********************
% %TL plots
    allplots('TLplots', R, f, TL, TLa, TLs, alpha1)
%
% %********************
% %NL plots
    allplots('NLplots', R, f, ws, D, NLwind, NLship, NLturb, NLtherm, NLtotal,
NL)
%
% %********************
% %Relative SNR
  allplots('relSNRplots', R, f, ws, D, relSNR)
%
% %********************
% %Link Margin plots
    allplots('linkmarginplots', R, f, linkmargin, depth)
%
```

B. INITIALIZE SUBROUTINE

```matlab
function [f,R,depth,ws,D,Pe,nu,L] = initialize
%***************************
%Initialize Data
%***************************
 clear all; clc;
%***************************
%Define Range and Frequency Limits:
%frequencies of interest (Hz)
f_upper = 100000;
```

38

```matlab
f_lower = 0;
f_res = 50;


%ranges and depth (m)
depth = 220;
range = 1500;
range_res = 10;
%**********************************
%Generate Frequency and Range vectors:
%  BW = f_upper - f_lower;
%
%  stop = ceil(log10(f_upper+1));
%  for i = 1:stop;
%      f(:,i) = [ (1*10^(i-1)) : (f_res*10^(i-1)): (9.99*10^(i-1)) ]';
%  end
%  f = reshape(f,9*i/f_res,1);
%  begin = find(f==f_lower);
%  finish = find(f==f_upper);
%
%  f = f(begin:finish);
f=(f_lower:f_res:f_upper);
f=f';
R = [0:range_res:range]; R(1)=1;
%***************************
%Define noise related parameters
%wind speed in m/s
ws=25;
%shipping activity low (D=0), med (D=0.5), high (D=1)
D=0.5;
```

C.   TRANSMISSION LOSS SUBROUTINE

```matlab
function [TL, TLattenuation, TLspreading, alpha1] = transmissionloss(R, f, depth)
%***************************
% TRANSMISSION LOSS
```

```matlab
%***************************
%*******************************************
%TL due to Spreading - Matrix (Range x Freq)
Rindex1 = find(R==depth);   %max range of spherical spreading
%Rindex2 = find(R==depth);   %max range of transitional spreading
Rindex3 = find(R==depth);   %max range of cylindrical spreading
TLspreading1 = 20*log10(R(1:Rindex1));
TLspreading3 = (10*log10(R(Rindex1+1:end))-10 *log10(R(Rindex1))) + TLspreading1(end);
TLspreadingtotal = [TLspreading1 TLspreading3];
TLspreading = TLspreadingtotal;
for findex = 2:length(f)
    TLspreading = [TLspreading; TLspreadingtotal];
end
%*********************************************
%TL due to Attenuation - Matrix (Freq x Range)
%using eqn from Urick p 108
%note this is given in dB/kyd with f in kHz therefore need to convert

fkhz = f./1000;
alpha1 = ((0.11.*(fkhz.^2)) ./ (1 + (fkhz.^2))) + ((44.*(fkhz.^2)) ./ (4100 + (fkhz.^2))) + ((3.0.*(10.^(-4))).*(fkhz.^2)) + 0.0033;

for Rindex = 1:length(R)
    for findex = 1:length(f);
        TLattenuation(findex,Rindex) = alpha1(findex).*R(Rindex).*1e-3;
    end
end
%*********************************************
%Total Transmission Loss Matrix
TL = TLattenuation + TLspreading;
TL=-TL;
```

D. NOISE LEVEL SUBROUTINE

function [NLwind, NLship, NLturb, NLtherm, NLtotal, NL] = noiselevel(R, f, ws, D)

%*****************************
% NOISE LEVEL
%*****************************
fkhz = f./1000;
%********************
%NL due to Surface Waves Option 2 frin
NLwind = (50 + (7.5.*(ws.^0.5)) + (20.*log10(fkhz)) - (40.*log10(fkhz + 0.4)));

%NL due to Shipping
NLship = (40 + (20.*(D-0.5)) + (26.*log10(fkhz)) - (60.*log10(fkhz + 0.03)));

%NL due to Turbulence
NLturb = (17 - (30.*log10(fkhz)));

%NL due to thermal noise in the receiver
NLtherm = (-15 + (20.*log10(fkhz)));

%Rain
%Industrial Noise
%Biologics
%*********************
%Total Noise Level
NLtotal = 10.*log10((10.^(NLwind./10)) + (10.^(NLship./10)) + (10.^(NLturb./10)) + (10.^(NLtherm./10)));

NL = NLtotal;
for Rindex = 2:length(R)
    NL = [NL NLtotal];
end
NL=-NL;

E. SOURCE LEVEL SUBROUTINE

```
function [PSL] = sourcelevel(R, f)
%*****************************
% Source Level
%*****************************
%SL = 171.5 + 10.*log10(Pe) + 10.*log10(nu);
SL=179
SL = SL.*ones(length(f),length(R));
PSL= SL-10*log(32);
```

F. PLOTS SUBROUTINE

```
function varargout = allplots(plots,varargin)
switch plots
case 'TLplots'
    % When the function allplots is called in linkbudgeteqnv4.m, this
    % section plots the Transmission Loss
    % It takes in the Range (R), Frequency (f), Total Transmission Loss (TL),
    % Transmission Loss due to attenuation (TLa), Transmission Loss due to
    % spreading (TLs) and the Attenuation coefficient


    R=varargin{1}; f=varargin{2}; TL=varargin{3}; TLa=varargin{4};
TLs=varargin{5}; alpha1=varargin{6};
    %logarithmic plot Spreading Transmission Loss (in dB) vs Range (in m)
    figure(1)
    semilogx(R,TL(1,:)); title('Total Transmission Loss'); grid on;
    xlabel('Range (m)'); ylabel('dB');
    %logarithmic plots the attenuation coefficient vs freq (in kHz)
    figure(2)
    semilogy(f/1000,alpha1);
    %title('attenuation coeff');
    grid on;
    xlabel('Freq (kHz)'); ylabel('dB/Km');
    xlim([1 100]);
```

%plots a 3-dimensional graph of Range (in m) vs freq (in kHz) vs

%Transmission Loss due to attenuation (in dB)

%   figure(3)

%   pcolor(R,f/1000,TLa);

%   shading interp;

%   colorbar;

%   hold on;

%   [cs, h] = contour(R, f/1000, TLa, [-100:10:200], 'k');

%   clabel(cs);

%   xlabel('Range (m)'); ylabel('Freq (kHz)'); zlabel('dB');

%   %title('TLattenuation in dB');

%   grid on;

%   hold off;

%   grid on;

  %plots a 3-dimensional graph of Range (in m) vs freq (in kHz) vs Total

  %Transmission Loss (in dB)

%   figure(4)

%   pcolor(R,f/1000,TL);

%   caxis([-80 -40])

%   shading interp;

%   colorbar;

%   hold on;

%   [cs, h] = contour(R, f/1000, TL, [-200:20:200], 'k');

%   %clabel(cs);

%   xlabel('Range (m)'); ylabel('Freq (kHz)'); zlabel('dB');

%   title('TL total in dB');

%   hold off;

%   grid on;

case 'NLplots'

  %When allplots is called in linkbudgeteqnv4.m, this section plots the

  %Noise Level

  %It takes in the Range (R), freq (f), wind speed (ws), Directivity (D0,

%Noise Level due to wind (NLwind), Noise level due to shipping

%(NLship), Noise level due to surface turbulence (NLturb), Noise Level

%due to thermal relaxation (NLtherm), Total Noise level (NLtotal),

%Total Noise Level in matrix form (NL)

R=varargin{1}; f=varargin{2}; ws=varargin{3}; D=varargin{4};
NLwind=varargin{5}; NLship=varargin{6};

NLturb=varargin{7}; NLtherm=varargin{8}; NLtotal=varargin{9};
NL=varargin{10};

%logarithmic plot of the various noise sources and total noise (in dB) vs freq (in kHz)

figure(5)

semilogx(f/1000,NLwind,'b',f/1000,NLship,'r',f/1000,NLturb,'g',f/1000,NLtherm,'c',f/1000,NLtotal,'k');

%title('NL in dB');

grid on;

xlabel('Freq (kHz)'); ylabel('dB');

legend('wind', 'shipping', 'turbulence', 'thermal', 'total');

ylim([0 110]);

xlim([0 100]);

%gtext({sprintf('wind speed: %2.1f m/s', ws),...

    %sprintf('Shipping coeff (D): %2.1f', D)});

% logarithmic plot of total Noise level (in dB) vs freq (in kHz)

%   figure(6)

%   semilogx(f/1000,NLtotal); title('NLtotal in dB'); grid on;

%   xlabel('Freq (kHz)'); ylabel('dB');

%

case 'relSNRplots'

%when allplots is called from linkbudgeteqnv4.m this portion plots the

%relative Signal to Noise Ratio

% it takes in range (R), freq (f), wind speed (ws), directivity (D),

% and relative Signal to noise Ratio (relSNR)

R=varargin{1}; f=varargin{2}; ws=varargin{3}; D=varargin{4};
relSNR=varargin{5};

```
        %plots the range in 1 km increments vs relative SNR
%    figure(7);
%    R1k=R(11); R2k=R(21); %R5k=R(51); R10k=R(101); R20k=R(201);
%    plot(f/1000,relSNR(:,11),'k',f/1000,relSNR(:,21),'g');
%    %,f,relSNR(:,51),'b',f,relSNR(:,101),'c',f,relSNR(:,201),'r');
%    grid on;
%    xlabel('Freq (kHz)'); ylabel('dB');
%    %title('Total Envirnmentals to Overcome');
%    legend('1 km', '2 km', '5 km', '10 km', '20 km');
%    %gtext({sprintf('wind speed: %2.1f m/s', ws),...
%    %      sprintf('Shipping coeff (D): %2.1f', D)});
    %plots a 3- dimesional graph of range (in m) vs freq (in kHz) vs
    %relative SNR (in dB) usin g a color range from -160 dB to -120 dB
    figure(8)
    pcolor(R,f/1000,relSNR);
    shading interp;
    caxis([-120 -80]);
    colorbar;
    hold on;
    [cs, h] = contour(R, f/1000, relSNR,[-200:20:200],'k');
    clabel(cs);
    xlabel('Range (m)'); ylabel('Freq (kHz)'); zlabel('dB');
    title('Total Environmentals to Overcome in dB');
    hold off;

case 'linkmarginplots'
    %when allplots is called in linkbudgeteqnv4.m, this part plots the link
    %budget margin
    %It takes in range (R), frequency (F), link margin (linkmargin), and
    %depth (depth)
```

```matlab
R=varargin{1}; f=varargin{2}; linkmargin=varargin{3}; depth=varargin{4};

%this plots a 3-dimensional graph of range (in m) vs freq (in kHz) vs
%linkmargin (in dB)
figure(9)
pcolor(R,f/1000,linkmargin);
shading interp;
colorbar;
hold on;
[cs, h] = contour(R,f/1000, linkmargin, [17.8 17.8], 'r');
%clabel(cs);
xlabel('Range (m)'); ylabel('Freq (kHz)'); zlabel('dB');
title('Link Margin in dB');
hold off;
end
```

G. PLOTTING WIND VS. TIME, RANGE VS. TIME, WIND VS. RANGE

```matlab
%u and v are components of wind, and the time must be converted into
%decimal values for day; the text file contains the forcast wind data
load u2004110712.txt
u=u2004110712(1:12,6);
v=u2004110712(1:12,7);
tautemp=u2004110712(1:12,5);

tautemp=(12+tautemp)/24+10;
uvtemp=sqrt(u.^2+v.^2);
load windseries
wspd = [wspd' uvtemp(1:11)']';
jdate = [jdate' tautemp(1:11)']';
save windseries wspd jdate

%Prof. Rice's wind observations
```

```
ricewind=[15.4 15.4 10.3 15.4 15.4 10.3 7.7 5.1 7.7];
ricetime=[1:9];


load Narra_wind.mat
load Narra_time.mat



figure(2)
plot(ricetime,ricewind,'r:')
title('Wind Speed vs Day'), xlabel('Day'), ylabel('Wind Speed (m/s)')
hold on
plot(jdate,wspd,'-.')
plot(Narra_time,Narra_wind,'g--')


%need to read in the range data from excel
%need file 'thesis data.xls' and sheets 'utility range' and 'data range'


Utility=xlsread('Thesis Data.xls','Utility Packets');
Data=xlsread('Thesis Data.xls','Data Packets');


load dat.mat
load util.mat


figure(101)
subplot(3,1,1)
plot(jdate, wspd)
title('Forecast Wind Speed Data vs. Time')
ylabel('Wind Speed (m/s)')
subplot(3,1,2)
plot(ricetime,ricewind)
title('Prof Rice Observed Wind Speed Data vs. Time')
ylabel('Wind Speed (m/s)')
subplot(3,1,3)
```

```
plot(Narra_time,Narra_wind*0.514)
title('Narragansett Observed Wind Speed Data vs. Time')
ylabel('Wind Speed (m/s)'),xlabel('Time (days)')

figure(3)
scatter(util(:,1),util(:,2),4)
xlabel('Day'),ylabel('Range (km)'),title('Utility Packet Range vs Time')

figure(4)
scatter(dat(:,1),dat(:,2),4)
xlabel('Day'),ylabel('Range (km)'),title('Data Packet Range vs Time')

%Need to get both wind speed and range on the same time scale for forecast
%data
%double for loop to synchronize time scales
for i = 1:463
   for j = 1:220
      if jdate(j) >= dat(i,1);
         windvalue(i) = wspd(j-1);
         break
      end
   end
end

%repeat loop for utility packets
for i = 1:656
   for j = 1:220
      if jdate(j) >= util(i,1);
         windvalue2(i) = wspd(j-1);
         break
      end
   end
end
```

```
save windvalue
save windvalue2


%get range and windspeed on same time scale for Prof Rice's observations
for i = 1:656
    for j = 1:9
        if ricetime(j) >= util(i,1);
            windvalue3(i) = ricewind(j-1);
            break
        end
    end
end


for i = 1:463
    for j = 1:9
        if ricetime(j) >= dat(i,1);
            windvalue4(i) = ricewind(j-1);
            break
        end
    end
end


%Need to get both wind speed and range on the same time scale for M/V
%Narragansett observations
%double for loop to synchronize time scales
for i = 1:463
    for j = 1:30
        if Narra_time(j) >= dat(i,1);
            windvalueN_D(i) = Narra_wind(j-1);
            break
        end
    end
end
```

```
%repeat loop for utility packets
for i = 1:656
    for j = 1:30
        if Narra_time(j) >= util(i,1);
            windvalueN_U(i) = Narra_wind(j-1);
            break
        end
    end
end
save windvalueN_U
save windvalueN_D


figure(5)
scatter(windvalue,dat(:,2),5)
title('Data Packet Range vs Forecast Wind Speed')
ylabel('Data Packet Range (km)'),xlabel('Wind Speed (m/s)')

figure(6)
scatter(windvalue2,util(:,2),5)
title('Utility Packet Range vs Forecast Wind Speed')
ylabel('Utility Packet Range (km)'),xlabel('Wind Speed (m/s)')

figure(7)
plotyy(dat(:,1),dat(:,2),dat(:,1),windvalue)

figure(8)
plot(ricetime,ricewind,util(:,1),util(:,2),'*')
title('Utility Packet Range and Observed Wind vs Time')
xlabel('Day')

figure(9)
```

```
plot(ricetime,ricewind,dat(:,1),dat(:,2),'*')
title('Data Packet Range and Observed Wind vs Time')
xlabel('Day')

figure(10)
scatter(windvalueN_D,dat(:,2),'*')
title('Data Packet Range vs. M/V Narragansett Wind Speed')
ylabel('Data Packet Range (km)'),xlabel('Wind Speed (m/s)')

figure(11)
semilogy(windvalueN_U,util(:,2),'*')
title('Utility Packet Range vs. M/V Narragansett Wind Speed')
ylabel('Utility Packet Range (km)'),xlabel('Wind Speed (m/s)')
```

H.   WEIGHTING WIND VS. RANGE AND PLOTTING

```
%program to weight range vs. wind speed plot

clear all; clc; close all;

load util.mat
load dat.mat
load windvalueN_U
load windvalueN_D
load Narra_time
load Narra_wind

weightU=zeros(13,9);
weightD=zeros(13,9);

ranges=[2 5 7 12 15 19 23 27 30 35 37 41 42];
windspeed=[Narra_wind(12) Narra_wind(8) Narra_wind(16) Narra_wind(18)
Narra_wind(9) Narra_wind(15) Narra_wind(1) Narra_wind(4) Narra_wind(2)];
```

51

```
for a=1:13
    for b=1:9
        for c=1:656
            if ranges(a)==util(c,2)
                if windspeed(b)==windvalueN_U(c)
                    weightU(a,b)=weightU(a,b)+1;
                end
            end
        end
    end
end

figure(12)
axis([2 16 0 45]),title('Weighted Utility Packet Range vs. Wind Speed')
ylabel('Utility Packet Range (nm)'),xlabel('Wind Speed (m/s)')
for a=1:13
    for b=1:9
        if weightU(a,b)>0
            hold on
            scatter(windspeed(b),ranges(a),weightU(a,b)*4,'b','filled')
        end
    end
end
scatter(windvalueN_U,util(:,2),1)
ninetylineU=[ranges(9) ranges(8) ranges(8) ranges(8) ranges(8) ranges(6) ranges(4)];
fiftylineU=[ranges(7) ranges(6) ranges(6) ranges(6) ranges(4) ranges(4) ranges(2)];
windspeed2=[windspeed(3) windspeed(4) windspeed(5) windspeed(6) windspeed(7) windspeed(8) windspeed(9)];
plot(windspeed2,ninetylineU,'r')
plot(windspeed2,fiftylineU,'g')
```

```
for a=1:13
   for b=1:9
      for c=1:463
         if ranges(a) ==dat(c,2)
            if windspeed(b)==windvalueN_D(c)
               weightD(a,b)=weightD(a,b)+1;
            end
         end
      end
   end
end

figure(13)
axis([2 16 0 45]),title('Weighted Data Packet Range vs. Wind Speed')
ylabel('Data Packet Range (nm)'),xlabel('Wind Speed (m/s)')
for a=1:13
   for b=1:9
      if weightD(a,b)>0
         hold on
         scatter(windspeed(b),ranges(a),weightD(a,b)*4,'b','filled')
      end
   end
end
scatter(windvalueN_D,dat(:,2),1)
ninetylineD=[ranges(9) ranges(6) ranges(8) ranges(8) ranges(8) ranges(5)
ranges(5)];
fiftylineD=[ranges(6) ranges(6) ranges(6) ranges(4) ranges(4) ranges(4)
ranges(2)];
plot(windspeed2,ninetylineD,'r')
plot(windspeed2,fiftylineD,'g')

%repeat weighting, for forecast data
load windseries
```

```
weightUF=zeros(13,220);
weightDF=zeros(13,220);

wspd=sort(wspd);

for a=1:13
    for b=1:220
        for c=1:656
            if ranges(a)==util(c,2)
                if wspd(b)==windvalue2(c)
                    weightUF(a,b)=weightUF(a,b)+1;
                end
            end
        end
    end
end

for a=1:13
    for b=1:220
        for c=1:463
            if ranges(a)==dat(c,2)
                if wspd(b)==windvalue(c)
                    weightDF(a,b)=weightDF(a,b)+1;
                end
            end
        end
    end
end

ninetylineUF=[ranges(9) ranges(10) ranges(6) ranges(8) ranges(9)];
fiftylineUF=[ranges(6) ranges(8) ranges(4) ranges(5) ranges(6)];
lines=[3 4 5 6 7];
```

```
figure(14)
axis([2 9 0 45]),title('Weighted Utility Packet Range vs. Forecast Wind Speed')
ylabel('Utility Packet Range (nm)'),xlabel('Wind Speed (m/s)')
for a=1:13
    for b=1:220
        if weightUF(a,b)>0
            hold on
            scatter(wspd(b),ranges(a),weightUF(a,b)*4,'b','filled')
        end
    end
end
plot(lines,ninetylineUF,'r')
plot(lines,fiftylineUF,'g')


ninetylineDF=[ranges(9) ranges(10) ranges(6) ranges(8) ranges(8)];
fiftylineDF=[ranges(6) ranges(8) ranges(4) ranges(4) ranges(6)];


figure(15)
axis([2 9 0 45]),title('Weighted Data Packet Range vs. Forecast Wind Speed')
ylabel('Data Packet Range (nm)'),xlabel('Wind Speed (m/s)')
for a=1:13
    for b=1:220
        if weightDF(a,b)>0
            hold on
            scatter(wspd(b),ranges(a),weightDF(a,b)*4,'b','filled')
        end
    end
end
plot(lines,ninetylineDF,'r')
plot(lines,fiftylineDF,'g')
```

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Hansen, Joseph T., *Link Budget Analysis for Undersea Acoustic Signaling*, MS Thesis, Naval Postgraduate School, Monterey, CA, June 2002

Jensen, F.B., Kuperman, W.A., Porter, M.B., Schmidt, H., (2000) *Computational Ocean Acoustics* (Springer-Verlag New York Inc. 2000)

Kotsch, William J., (1970) *Weather for the Mariner* (Naval Institute Press, 1977)

Kinsler, L.E., Frey, A.R., Coppens, A.B., Sanders, J.V. (2000). *Fundamentals of Acoustics* (John Wiley & Son, Inc., 2000).

Medwin, Herman, Clay, Clarence S., (1998). *Fundamentals of Acoustic Oceanography* (Academic Press 1998)

Reddy, M.P.M. (2001) *Descriptive Physical Oceanography* (A.A. Balkema Publishers, 2001)

Rice, Joseph A. *Seaweb Acoustic Communication and Navigation Networks* from Proceedings of the International Conference "Underwater Acoustic Measurements: Technology and Results" Heraklion, Crete, Greece 28th June-1st July 2005

Ross, Donald (1987) *Mechanics of Underwater Noise* (Peninsula Publishing, 1987)

Shannon, C.E., Weaver, W. (1949) *A Mathematical Theory of Communication* (Univ. of Illinois Press, Urbana, IL. 1949)

Urick, Robert (1986) *Ambient Noise in the Sea* (Peninsula Publishing, 1986)

Urick, Robert (1983) *Principles of Underwater Sound for Engineers 3rd. Edition* (McGraw-Hill, Inc. 1983)

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Joseph A. Rice
   Department of Physics
   Naval Post Graduate School
   Monterey, CA

4. CDR Rebecca Stone, USN
   Department of Oceanography
   Naval Post Graduate School
   Monterey, CA

5. ENS Christopher Hurt
   Glenview, IL

6. CDR Van Gurley, USN
   Naval Meteorology and Oceanography Command
   Stennis Space Center, MS

7. CAPT John Cousins, USN
   Executive Office
   Naval Oceanographic Office

8. CAPT Jonathan White, USN
   Fleet Numerical Meteorology and Oceanography Center
   Monterey, CA

9. Dr. Thomas Swean
   ONR 321OE
   Arlington, VA

10. CAPT Gunnar Galsgaard, USN
    PEO IWS 5
    Washington, D.C.

11.   Dr. Allen Moshfegh
      DARPA IXO
      Arlington, VA

12.   CDR Melissa Smoot, USN
      PEO OMW, PMS NSW
      Washington, D.C.

13.   Newell Hurt
      SunGard Systems
      Chicago, IL